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Characterization of the Steady Wave Field of the High Speed Transom Stern Ship – Model 5365 Hull Form

by

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A model of the R/V Athena hull form (Model 5365) was towed on Carriage 1 of the David Taylor Model Basin at the Naval Surface Warfare Center (NSWCCD.) The R/V Athena is a converted PG-84 Asheville-class patrol gunboat. Measurements of the free-surface were made using various instrumentation systems, including conductivity probes in the stern region, Quantitative Visualization in the bow and shoulder wave region, and wave capacitance probes for stationary measurements of the transverse wave field. Video cameras were also used to qualitatively characterize the wave field and compare it with video of the full-scale vessel.

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CONTENTS

FIGURES

TABLES

NOMENCLATURE

A/D............Analog to digital
B_T.............Maximum transom beam
CFD.......... Computational fluid dynamics
C_T.............Total drag coefficient
C_W............Wave resistance coefficient
Fr...............Froude Number
Fx...............Total resistance
L...............Model length between perpendiculars
ONR...........Office of Naval Research
QViz..........Quantitative Visualization
X...............Longitudinal position
Y...............Transverse position

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ABSTRACT

A model of the R/V Athena hull form (Model 5365) was towed on Carriage 1 of the David Taylor Model Basin at the Naval Surface Warfare Center, Carderock Division (NSWCCD.) The R/V Athena is a converted PG-84 Asheville-class patrol gunboat. Measurements of the free-surface were made using various instrumentation systems, including conductivity probes in the stern region, Quantitative Visualization in the bow and shoulder wave region, and wave capacitance probes for stationary measurements of the transverse wave field. Video cameras were also used to qualitatively characterize the wave field and compare it with video of the full-scale vessel.

ADMINISTRATIVE INFORMATION

The work described in this report was performed by two divisions of the Hydromechanics Directorate at the Naval Surface Warfare Center, Carderock Division (NSWCCD). The collaborating groups were the Maneuvering and Control (Code 5600) and Resistance and Powering (Code 5200) Divisions. The work was sponsored by the Office of Naval Research as part of the Ship Wavebreaking and Bubbly Wake Program. The ONR Program Manager is Dr. L. Patrick Purtell (Code 334). The Project Leader at NSWCCD is Dr. Thomas Fu (Code 5600). This work was funded under Funding Document No. N0001405WX2017 and performed under Work Unit: 05-1-5600-326.

INTRODUCTION

Computational Fluid Dynamics (CFD) codes have demonstrated increasing fidelity in predicting the large-scale Kelvin wave structure for a variety of craft. However, except perhaps for computationally-intensive high-resolution models constructed specifically for that purpose, CFD codes do not, in general, reproduce the short-scale surface evolution or the energy dissipation and turbulence of the breaking wave regions of ship generated wave fields. Since the energy in breaking and other nonlinear events is not redistributed in a consistent manner, wave amplitudes can be over predicted. In the past, the regions of breaking predicted by codes were, in fact, dependent on the specific empirically-based breaking criteria assumed. More recently developed higher-order CFD codes, utilizing level-set and volume-of-fluid schemes to handle the free-surface, may in fact, when run with sufficient resolution, be able to predict these breaking regions.

In order to improve the correspondence of CFD code predictions to the full-scale phenomena (while keeping the computational load tractable), we must focus on understanding how the extent of breaking and nonlinear events may be better accommodated within the existing model framework and, ultimately, on how the crucial aspects of energy redistribution can best be reproduced. By employing model-scale

measurements in a controlled environment, we can bridge the gap between CFD predictions and full-scale behavior in the wake region. That is, model-scale measurements can be utilized to characterize the mean elevation and surface roughness in the Kelvin wave system, and thereby to deduce the distribution of breaking and energy dissipation. This in turn can be compared to CFD predictions: first, to evaluate how various breaking criteria employed in potential flow codes either increase or decrease the correspondence of predicted breaking regions to the model-scale measurements of breaking; and second, to evaluate how higher-order CFD provides a better match when applied in nonlinear regions of the wake. It is this strategy that the Office of Naval Research (ONR) Ship Wavebreaking and Bubbly Wake Program has undertaken in 2004-2005, and the work described herein is part of that effort.

In 2004, as part of the ONR Ship Wavebreaking Workshop & Review, a focused effort was made to assess the CFD capability as applied to ship generated waves and wave breaking. Predictions of the wave field around Model 5365 were made by four separate groups, utilizing five CFD codes. One code, CFDSHIP-IOWA (Wilson & Stern, 2005), was run by two different groups utilizing two distinct grids. All together, seven separate solution sets were submitted for each of the test conditions requested. This code evaluation effort will be reported in Fu et al*. Model testing was also performed and used to assess code performance and aid in code development. This report describes the model testing performed as part of this workshop.

Model 5365 was chosen as the hull form geometry to be utilized in this code evaluation and assessment effort. Model 5365 is a 1/8.25-scale model of the R/V Athena. The R/V Athena is a converted PG-84 Asheville-class patrol gunboat. It is capable of greater than 18 m/s (59 ft/s), or 35 knots, and has a high speed transom stern. This choice of geometry allowed for data to be obtained over a large Froude number range. The high-speed transom stern provided the opportunity to test and predict the wave field for both wet and dry transom conditions. By utilizing the Model 5365 hull form, we also enable comparison with full-scale phenomena, as there is also an ONR effort utilizing the R/V Athena I as a test platform, establishing a database of both qualitative and quantitative information at a variety of ship speeds. To correspond closely to this full-scale work, we have made model-scale measurements at 5.4, 9.3, 13.3, and 15.4 m/s (17.7, 30.4, 43.5, and 50.6 ft/s) or 10.5, 18, 25.8, and 30 knots. The model was tested unpropelled and unappended to simplify the CFD prediction task.

The objectives of this test were to:

- Measure the mean wave elevation and characterize the extent of breaking around Model 5365.
- Measure the total resistance and sinkage and trim of the hullform.
- Measure the far-field longitudinal wave field and compute wave resistance.

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* Fu, T.C., Pence, A.M., and Karion, A., "A Comparison of Predicted and Measured Ship (Model 5365) Generated Wave Fields and Resistance", to be published.

MODEL DESCRIPTION

Model 5365 is a wood and fiberglass model of the R/V Athena, first tested in 1979 as part of the First Workshop on Ship Wave-Resistance Computations. Due to the age and condition of the model, the model was patched, re-painted and measured to determine its actual geometry. Model and full scale hullform characteristics are shown in Table 1, and a body plan drawing of the hullform is shown in Figure 1. The model was tested unappended at a displacement which matched the displacement of the ***R/V Athena I*** during the 2004 ONR field test of that ship (Fu et al[+]), during which the ship was tested at a light load condition.

Figure 1: The R/V Athena I.

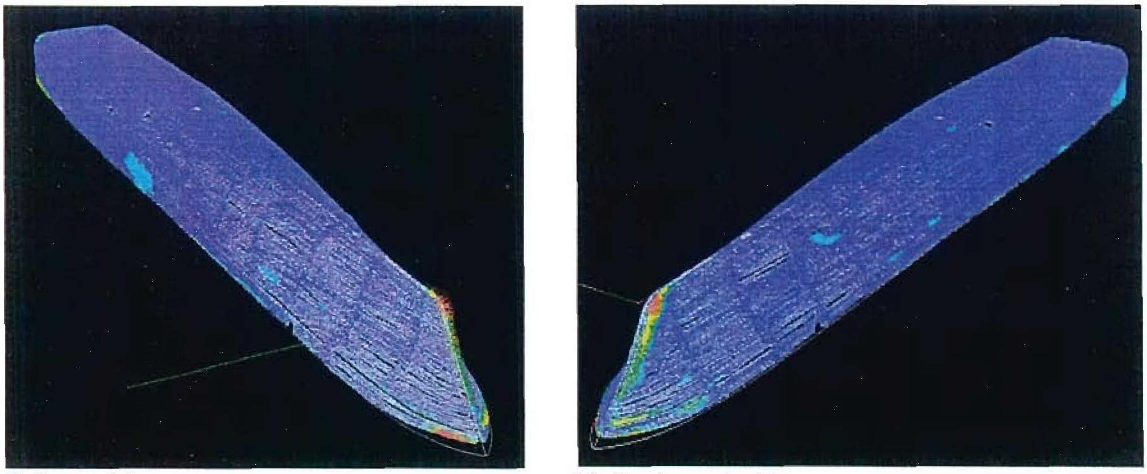
The detailed measurement of the model revealed an asymmetry in the hull near the bow. This asymmetry, which can be seen in Figure 2, is shallow (< 1 mm (0.04 in)), but is found near the bow on the starboard side of the model. The actual, as tested, detailed surface geometry of Model 5365 is available from NSWC by request. Figure 3 shows the transom and bow regions of the model. The model was painted black on the starboard side, to minimize laser reflections, and yellow on the port side, to aid in visualizing the breaking bow wave. Station markings and waterlines were also marked.

Table 1: Model 5365 and Full-Scale (R/V Athena) Hull Form Characteristics

	Model Scale	**Full Scale**
Displacement	397 kg (875 lbs)*	229 metric tons (225 long tons)
Draft (hull)	0.19 m (0.618 ft)*	1.7 m (5.5 ft)
Max. Draft (overall)		3.2 m (10.5 ft)
Maximum Beam	0.84 m (2.74 ft)	6.9 m (22.6 ft)
Transom Beam	0.70 m (2.3 ft)	5.8 m (19.0 ft)
LBP	5.69 m (18.67 ft)	46.9 m (154.0 ft)
Scale Ratio	8.25	

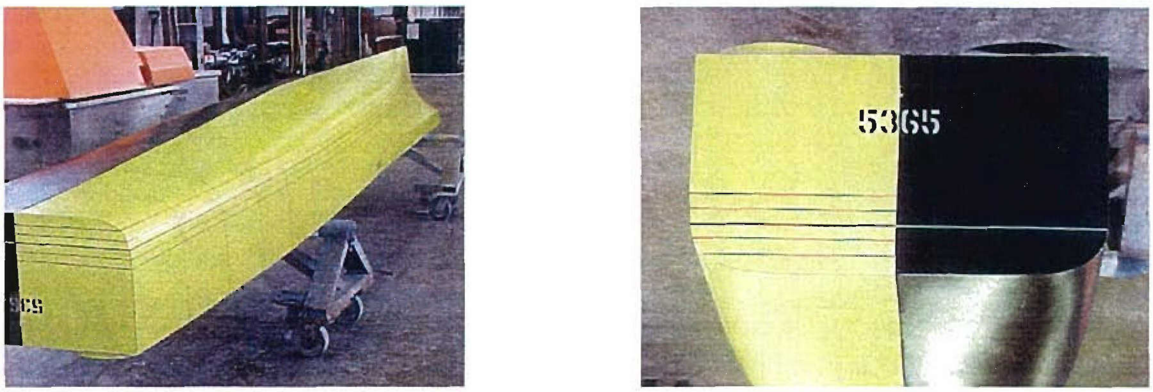
*As tested (model was ballasted to match the 2004 ONR Athena Field Test displ.).

[+] Fu, T.C., Ratcliffe, T., Walker, D.C., Rice, J., and Karion, A., "Field Measurement of the Bow Wave of the R/V Athena I", to be published.

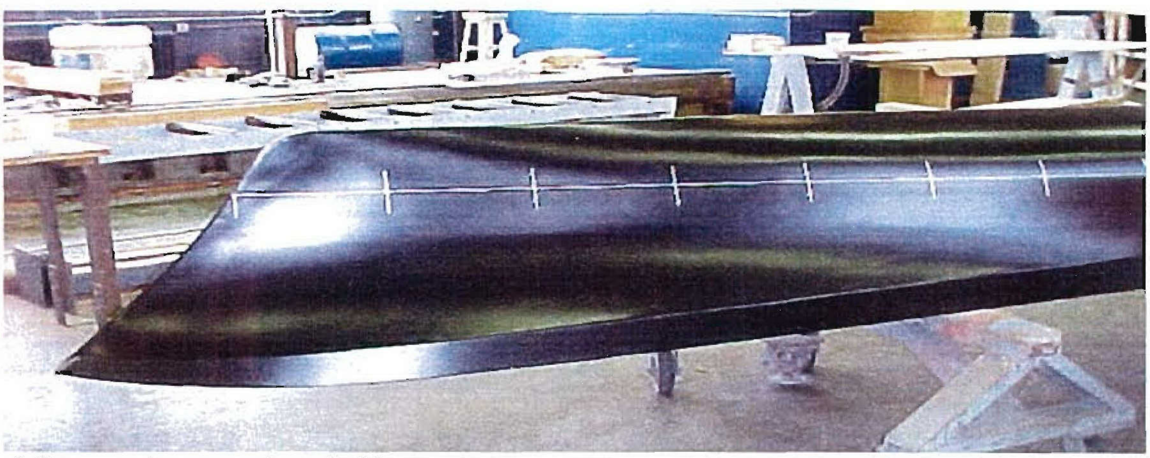


a) Port side. b) Starboard side.

Figure 2: Contour maps of the deviation (Blue =0.0, Red =1.0 mm (0.04 in)) from the design geometry for Model 5365.



a) Starboard side. b) Transom



c) Bow region – starboard side.

Figure 3: Images of Model 5365 showing the yellow and black paint scheme, waterlines, and station lines.

MEASUREMENT METHODS

Wave Cut Capacitance Probes (Longitudinal Wave Height Measurement)

Capacitance probes were used to determine wave heights. Wave cuts were obtained using a modified and strengthened capacitance wave probe system that was previously evaluated in the Circulating Water Channel at NSWC, Carderock Division.

Theory of Operation

The sensing element of the capacitance probe is a 30-gauge (AWG) solid silver-plated copper wire with 0.11 mm (0.045 in) kynar insulation, approximately 91 cm (36 in) in length. Attached to the sensing element is a weighted 1.2 m (4 ft) length of Mylar fishing line, used to provide probe stability in waves. The sensing element is suspended with half its length submerged in the basin. The basin water provides the ground reference for the sensing elements on the circuit card. With the copper wire completely insulated from the water, the sensing element behaves as a capacitor with one plate being the copper wire, the second plate the water, and the wire insulation acting as a dielectric. As waves in the basin change the submerged height of the sensing element, they change the effective capacitor plate size, which results in a change in capacitance. The change in capacitance is proportional to the wave height, which can then be calculated. By attaching the wave wire, a varying capacitor, to a timing circuit, a DC voltage is generated that is directly proportional to the capacitance of the probe and therefore, the wave height.

Experimental Setup

A truss section (wave boom), cantilevered from the basin wall over the water, provides a structure from which instrumentation is mounted, as shown in Figure 4. The wave boom extends 6.83 m (22.4 ft) from the basin wall, which is approximately 0.91 m (3 ft) short of the basin centerline. Mounted vertically on the wave boom is a motorized unislide traverse with an attached horizontal bar. The capacitance probes' electronics are mounted on the horizontal bar of the unislide. The unislide allows precise placement of the probes' vertical position, or probe emergence, used during static calibration of the probes. Four probes were used for this experiment. The position of the probes is referenced to the model centerline, with probe #1 being the closest inboard and probe #4 the farthest outboard. The probes' positions from the centerline of the model are given in Table 2:

Table 2: Capacitance Probe Transverse Position

Probe #	Distance from the Centerline (m (ft))	y/B_T
1	0.60 (1.98)	0.86
2	1.05 (3.45)	1.50
3	1.40 (4.60)	2.00
4	1.75 (5.75)	2.50

B_T = Maximum transom beam = 0.70 m (2.3 ft)

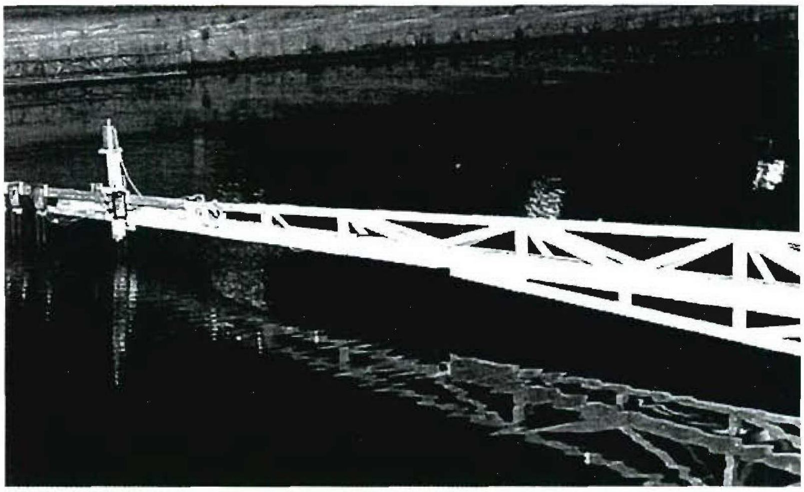


Figure 4: The Wave Boom which holds the capacitance wave probes

A photosensor is set to trigger data collection when the forward perpendicular of the model is a predefined distance (7.6 m (25.0 ft) in this case) from the capacitance probes. A 133-MHz Pentium-class personal computer, using an ADC488 16-bit analog-to-digital (A/D) converter, collects and stores the data.

The chief limitations of the capacitance probes are that the maximum wave height can exceed the sensing element range, and that a clearly defined water surface is required (i.e., spray or foam will not produce an accurate reading). They have been extensively validated and successfully utilized in numerous experiments over the years.

Calibration

In-situ calibrations are performed after the completion of the test setup. To calibrate the probes, the motorized unislide is traversed in 2.54-cm (1-in) increments for a total range of +/- 7.62 cm (3 in). Data are collected at each incremental step for each of the probes. A straight line fit is performed and a slope is calculated and stored for each probe. An in-situ calibration allows for the calibration of the probes, the signal conditioning amplifiers, and the A/D together as a system.

Operating Procedures

Probe zeroes are collected in calm water before each run. The model is then run through the test section, past the probes, at a constant speed. As the model approaches the test section, a strip of reflective tape positioned on the carriage triggers a photosensor placed at the side of the basin which starts data collection. The position of the photosensor and the duration of data collection were adjusted to ensure that the maximum amount of data was collected before tank wall reflections occurred. Data was filtered at 10 Hz with a 3 pole Bessel filter and collected at a sampling rate of 100 Hz for 20 to 30 seconds, depending on model speed.

Conductivity Finger Probes (Stern Topography)

Finger probes, which measure the height of the free-surface, were used to measure the stern topography behind the model.

Theory of operation

Conductivity finger probes were developed by Steve McGuigan at NSWCCD and are routinely used to characterize wave heights on the free surface. The finger probe is a vertically oriented, mechanized probe that continuously searches for the free surface. The sensing element of the probe is a 0.038 cm (0.015 in) diameter, 5 cm (2 in) long stainless steel wire. The wire is mounted into a copper tube, which makes up the body of the probe. A geared rack, attached to the probe body, allows the probe to be driven up and down in the vertical plane by a servomotor. Electrical continuity through the probe is sensed by an electronic circuit, which drives the servomotor. When the probe is not in contact with the water surface, there is no electrical continuity through the probe and the servomotor drives the probe toward the surface of the water. Once contact is made between the probe and the surface of the water (circuit ground), electrical continuity is sensed and the probe is driven up out of the water. This process is continuously repeated, causing the probe to oscillate at the free surface at approximately 10 Hz. The probe is also geared to a potentiometer to track its position along the z-axis (wave height). Probe position is only recorded by a sample and hold circuit during the instant the probe makes initial contact with the water surface. This manner of sampling probe position alleviates position error from meniscus effects due to surface tension.

Calibration

Static calibrations are performed on the conductivity probes in the lab, prior to the experiment. Probes are mounted together on a bracket, and attached to a unislide traverse. The probes are positioned over a container of water, and allowed to track the calm free surface as the unislide is traversed in 2.54 cm (1 inch) increments for a total range of +/- 7.62 cm (3 inches). Data are collected at each incremental step for each of the probes. A straight line fit is performed and the slope is calculated and stored for each probe.

Experimental Setup

To create a topographical map of the free surface at the stern of the model, four probes are mounted together with 5.1 cm (2 inch) spacing between probes. The set of probes is then attached to an X-Y traverse that is mounted horizontally to the carriage at the stern of the model, as shown in Figure 5. The frame allows an area of measurement with dimensions of 1.8 m X 2.7 m (6 ft X 9 ft). Two string pots are attached to the traverse and used to track the longitudinal (X) and transverse (Y) positions of the probes. A 33 MHz 486 class personal computer, using an ADC488 16 bit A/D converter, collects and stores the data. The collection computer is networked with a 350 MHz Pentium II class laptop computer which is used for data analysis and plotting.

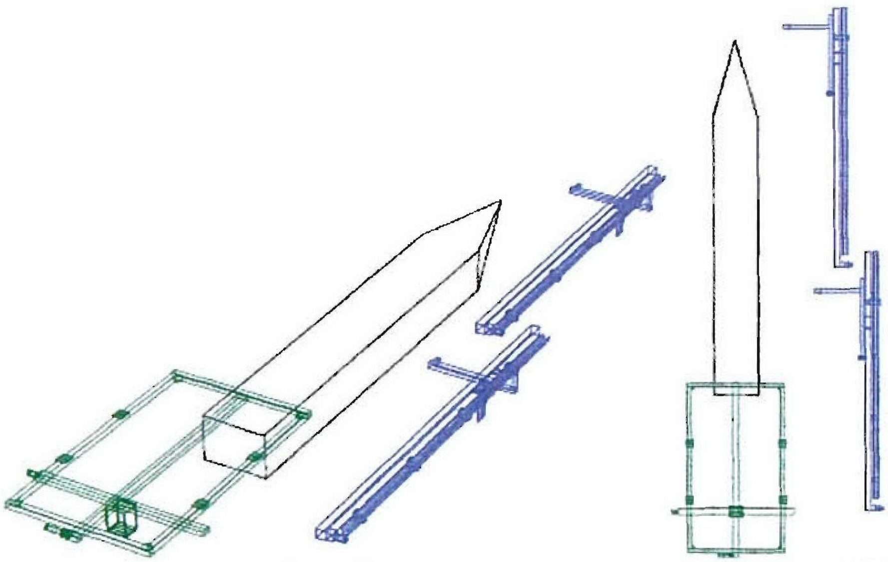


Figure 5: Schematic view of stern topography traverse (green) and QViz hardware (blue).

Operating Procedures

Finger probe #1 is aligned longitudinally (X) and transversely (Y) with the aft perpendicular and centerline of the model respectively. Longitudinal and transverse string pots are zeroed at this location, and all future measurements are referenced to this position. In order to collect the data needed to generate a complete topographical map of the stern area, the area is divided into a number of transverse cuts. The possible number of transverse cuts per run depends on model speed. Once the number of traverse cuts per run is determined, a command file is generated which controls the positioning of the probes during the run. Using four probes spaced 5.1 cm (2 in) apart along the x-axis, one transverse cut collects an area of 15 cm x 132 cm (6 in x 52 in). Starting as close to the stern of the model as possible (1.3 cm (0.5 in)), successive transverse cuts are made with an advancement of 20.3 cm (8 in) along the x-axis between cuts.

Prior to each run, a zero collection is performed. A zero run consists of performing an identical collection run of transverse cuts, but with the model sitting still. This allows bias errors, due to misalignment or sagging of the traverse's X-Y plane, to be removed. After the zero run is performed, the model is brought up to a constant speed and the collection of transverse cuts is started. This process is repeated at successive transverse locations until the desired stern area of the model has been completely mapped.

Quantitative Visualization (Free-Surface Elevation Mapping)

A non-intrusive optical technique, Quantitative Visualization (QViz), has been developed to measure the free-surface disturbances occurring in regions commonly inaccessible to more traditional measurement methods, i.e. near wake flows, bow sheets and breaking waves. These regions are generally difficult to quantify due to the multiphase aspect of the flow as well as their very unsteady nature. However, the

unsteady surfaces, droplets and bubbles in these regions are effective scatterers and allow for optical imaging of the deformations of the surface. Initially used to measure the wave field around ship models (Furey and Fu[1]), this technique has been used extensively to measure free-surface elevations and breaking waves (Fu et al.[2], Karion et al.[3]).

Technique Description

In QViz the free-surface is illuminated by a laser light sheet, generated by a scanning mirror or cylindrical lens, and imaged using a monochrome progressive scan camera (see Figure 6). The recorded digital images are then corrected for distortion and calibrated (see Figure 7). The corrected images are then processed to provide the free-surface elevation in the image plane of the camera. The free-surface elevation is determined by utilizing several edge detection image processing techniques. This image correction can be seen in Figure 7, where the image on the left is the original distorted image of the calibration grid (equally spaced dots in orthogonal lines) and the image on the right is the corrected image. Figure 8 shows the profile determined from the corrected, calibrated image overlaid on the image. The red line shows the smoothed profile, while the blue points show the extracted points determined by the edge detection algorithm. The current NSWCCD tow tank QViz system and its capabilities are described in detail in Rice, et al[4].

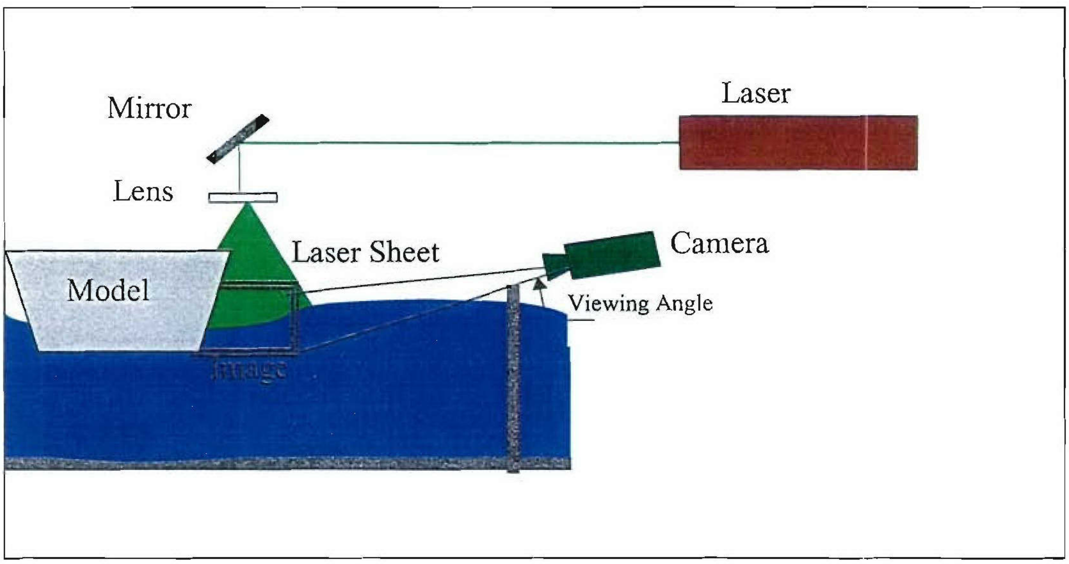


Figure 6: Sketch showing the generalized QViz set-up. The laser sheet can be generated from a cylindrical lens or scanning mirror.

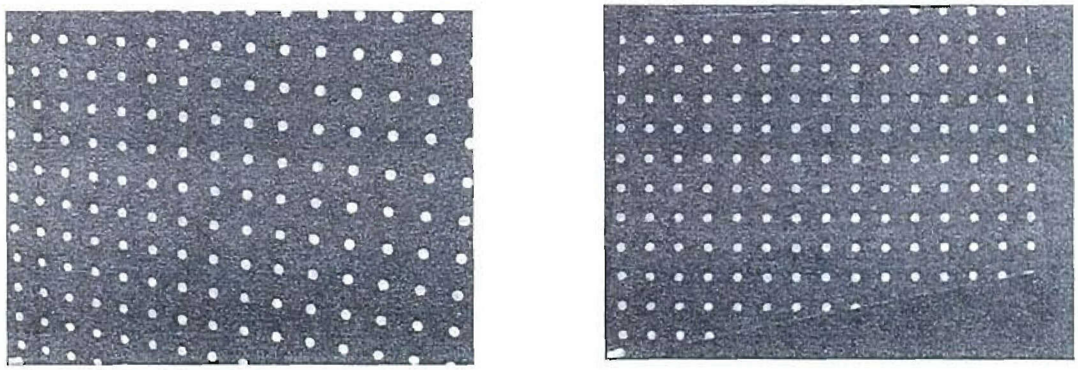


Figure 7: Images of a calibration grid: a) before calibration correction and b) after correction.

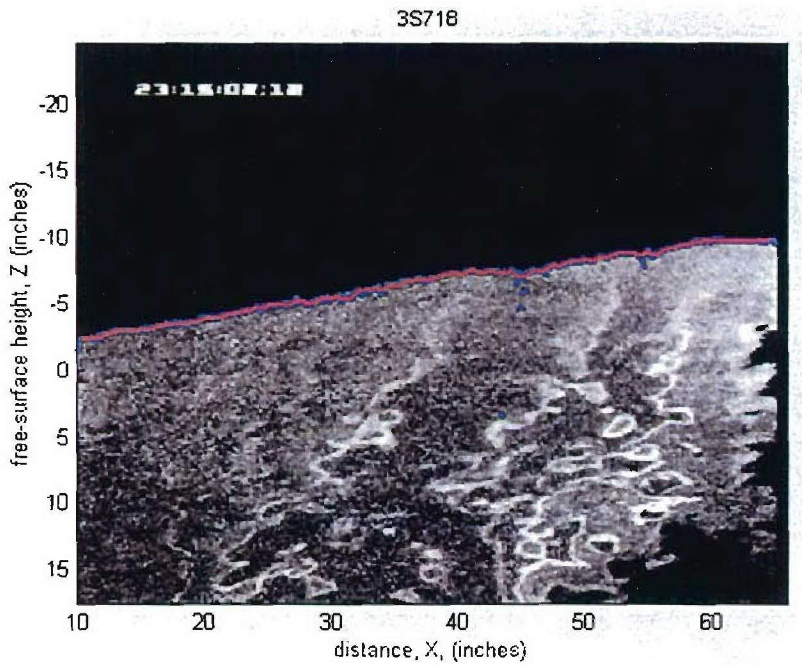


Figure 8: Sample QViz image showing the extracted free-surface profile: blue – extracted points, red-smoothed profile.

<u>Setup</u>

The QViz system consists of a continuous wave laser and optics to create a steerable light sheet. The light sheet and collection optics are mounted at a specific orientation relative to the flow. The laser beam is coupled into a fiber-optically fed light probe. For the current set up, two light sheets are generated perpendicular to the model center line and the free-surface, at two different axial locations (referred to as the forward location and the aft location). A digital video camera is directed towards each light sheet.

Images from each camera are collected at 30 frames/second using two National Instruments framegrabber boards and two personal computers (one for each camera). An

image analysis program was developed at NSWCCD using National Instruments Labview software and image processing toolbox to extract the surface profile information. Sequential images (usually 30 images, representing one second of data) are analyzed and then averaged together, providing a time-averaged profile.

Calibration

The video camera recording the images is looking down (tilt) at the free surface, and may also be oriented at a slight rotation (pan). To correct for distortion in the images, a calibration grid is videotaped at the same location as the laser sheet. A calibration algorithm from National Instruments' LabView IMAQ Vision package is used to calculate the equations necessary to correct the data images. This is automatically done in the LabView program used to analyze the images. A zero run is performed with the model at zero forward speed and the wave elevation zero. This calibration data set allows system bias to be removed.

Block Gages & String Potentiometers (Resistance, Sinkage & Trim)

Two calibrated 10-cm (4-in) block gages, one 45-kg (100-lb) and one 9-kg (20-lb), were used to measure the drag and side force, respectively.

Experimental Setup

A 91-kg (200-lb) tow post was positioned at station 5 in the model and a grasshopper was attached to the stern (see Figure 9). Mounted to the tow post was a 45-kg (100-lb), 10-cm (4-in), block gage to measure drag and a 9-kg (20-lb), 10-cm (4-in) block gage to measure side force. A pitch-roll gimbal (with fixed roll) joined the block gages to the model. Trim was measured using string potentiometers located at the bow and stern of the model. The distance between the string pots was 4.991 m (196.5 in). The forward string pot was located 0.552 m (21.75 in) aft of the Forward Perpendicular and the aft string pot was located 0.146 m (5.75 in) forward of the Aft Perpendicular.

Calibration

The block gages were calibrated by NSWCCD, Code 5200, following standard procedures. To measure sinkage and trim, each morning the zero reading was set on the string potentiometers, while the model floated on the quiescent surface. Ballasting was also checked at this time, by using the hook gages to assure that the model was floating at the zero waterline.

Operational Procedures

The resistance and side forces, as measured by the block gages, were recorded for each run by a 33 MHz 486 class personal computer, using an ADC488 16 bit A/D converter. This computer also recorded the string potentiometer readings and computed sinkage and trim.

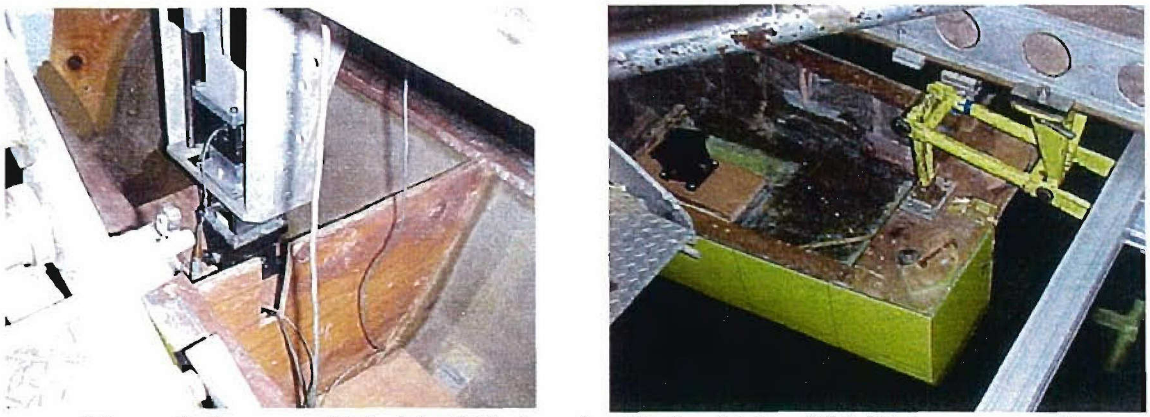


Figure 9: Images of Model 5365 rigged with a) a 91-kg (200-lb) tow post and b) a stern Grasshopper for sinkage and trim measurements.

TEST DESCRIPTION

The test was conducted 5-16 November, 2004, on Carriage 1, in the Shallow Water Towing Basin at NSWCCD. The tow tank is approximately 256 m (840 ft) long, 15.5 m (50.9 ft) wide, and 7 m (22 ft) deep. Carriage 1 has a speed range of 0.3 to 9.3 m/s (0.8 to 30.4 ft/s), or 0.5 to 18.0 knots, and the speed was monitored and recorded for each run, for the entire run. The model was newly painted and run without appendages (rudders, shafts, struts and propellers) or a trip wire.

Due to the number of desired measurements, there is significant risk in requiring simultaneous measurements, because the probability of a successful run is the product of all the individual success rates for each system involved. Additionally, there are conflicting parameters between the instrumentation systems, e.g. to increase the signal to noise ratio in the QViz images, low ambient light levels are desired, but light is needed for the standard video cameras used to visually characterize the wave field. Since the objective was time averaged data, it was prudent to divide the test into the following three parts.

Part 1: Measurement of Resistance and Sinkage and Trim

With the model rigged to be free to sink and trim, resistance and sinkage and trim were measured for model speeds ranging from 1.1 to 6.2 m/s (3.5 to 20.5 ft/s,) corresponding to full-scale speeds of 3.1 to 18 m/s (10.1 to 59.1 ft/s), or 6 to 35 knots. At least two runs were made at each speed.

Part 2: Wave Field Topography

The wave field topography measurements were made at four speeds. The 91-kg (200-lb) tow post and grasshopper were replaced by adjustable tow posts, allowing for the model to be run at fixed sinkage and trim. For each speed, the model was fixed at the sinkage and trim measured in Part 1 of the test for that speed. Specifying and setting the sinkage and trim provided for more control of the run to run variability and allowed for

the finger probes to be positioned more closely to the transom, since the model could not move into the probes as is possible when the model is free. At least two complete mappings were made at each of the four model speeds, 1.88, 3.22, 4.62, and 5.37 m/s (6.17, 10.58, 15.16, and 17.63 ft/s), corresponding to full-scale speeds of 5.4, 9.3, 13.3, and 15.4 m/s (17.7, 30.4, 43.5, and 50.6 ft/s), or 10.5, 18, 25.8 and 30 knots.

Part 3: Wave Cuts and Visual Characterization

Similar to Part 2, the model was held fixed in the correct position for each speed (the same four speeds as in Part 2) and the longitudinal wave field was measured by four capacitance probes from the wave boom. Three video cameras were also used to provide a visual record of the wave field for each speed.

RESULTS

Resistance and Sinkage and Trim

The measured resistance and sinkage and trim are shown in Figures 10 and 11, respectively, and given in Tables 3 and 4. Figure 10 also shows Model 5365 resistance data taken in 1979 (Jenkins[5]) and 1992 (included in Appendix A). The 1979 test was performed with a skeg; the 1992 test was done with the model in a fully-appended configuration, while the current (2004) test was performed on the bare hull. These configuration differences can be seen in the resistance curves and should have less effect on the sinkage and trim. Trim and sinkage are reported as displacement of the Forward and Aft perpendiculars from their zero speed position.

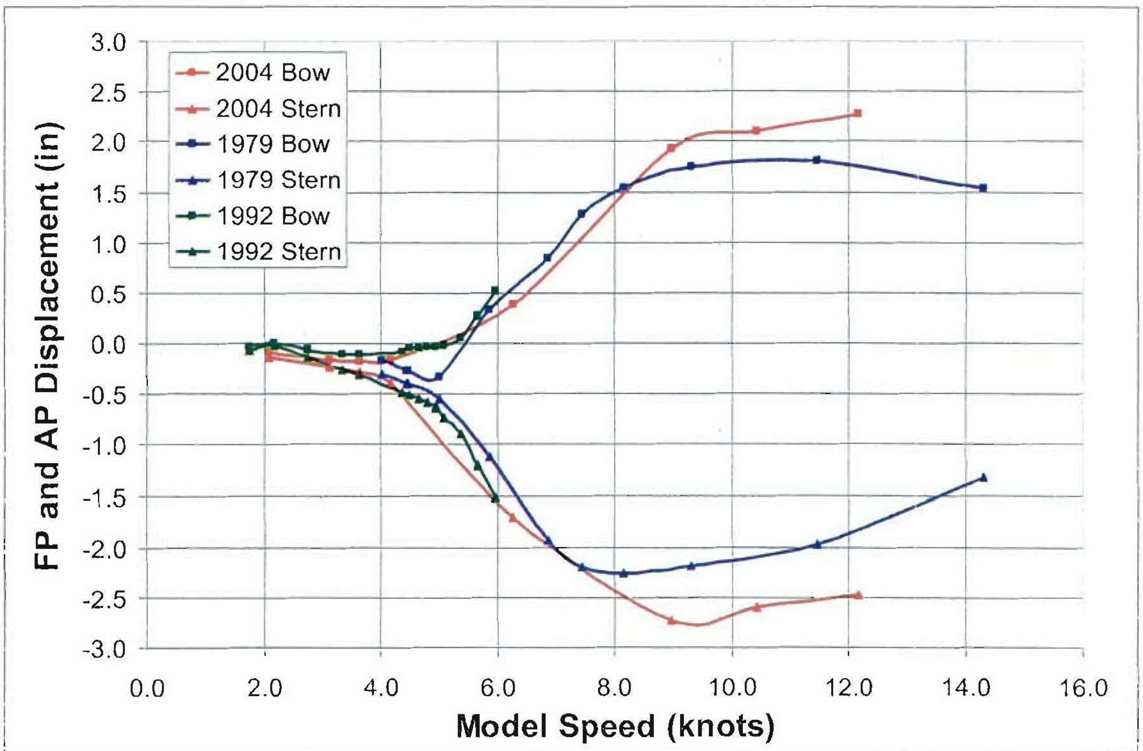


Figure 10: Sinkage and trim for Model 5365, described as the displacement of the Forward and Aft Perpendiculars from their zero speed position.

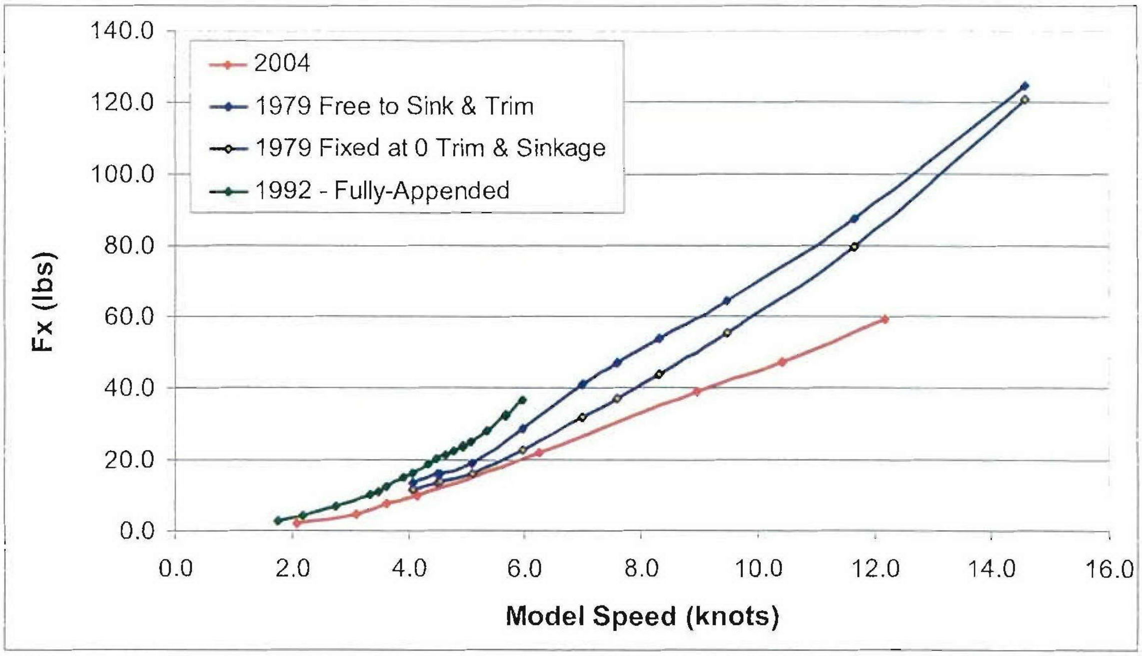


Figure 11: Total resistance (lbs) versus speed for Model 5365 for three different tests.

It should be noted that the 2004 resistance is significantly lower than the 1979 free to sink and trim data. Since in 2004 the model was tested at a lighter displacement the zero speed wetted surface areas are different for the two data sets. By computing C_T, the total drag coefficient, we can more meaningfully compare the 2004 to the 1979 data. At 1.88 m/s (6.17 ft/s), C_T=4.23 and 5.58, for 2004 and 1979, respectively. So there is a significant difference in the measured resistance between the 1979 and 2004 tests, even when the variation in wetted surface area is accounted for.

Table 3: Model 5365 Trim Data

Full-Scale Speed (m/s (ft/s, knots))	**Model-Scale Speed (m/s (ft/s, knots))**	**Forward Perpendicular Trim (cm (in))** + bow up, - bow down	**Aft Perpendicular Trim (cm (in))** + bow up, - bow down
3.1 (10.1, 6.0)	1.08 (3.53, 2.09)	-0.224 (-0.088)	-0.338 (-0.133)
4.6 (15.2, 9.0)	1.62 (5.30, 3.14)	-0.386 (-0.152)	-0.564 (-0.222)
5.4 (17.7, 10.5)	1.88 (6.17, 3.66)	-0.409 (-0.161)	-0.688 (-0.271)
6.2 (20.3, 12.0)	2.15 (7.06, 4.18)	-0.399 (-0.157)	-0.996 (-0.392)
9.3 (30.4, 18.0)	3.22 (10.58, 6.27)	0.983 (0.387)	-4.318 (-1.700)
13.3 (43.5, 25.8)	4.62 (15.16, 8.99)	4.902 (1.930)	-6.909 (-2.720)
15.4 (50.6, 30.0)	5.37 (17.63, 10.45)	5.364 (2.112)	-6.568 (-2.586)
18.0 (59.1, 35.0)	6.27 (20.57, 12.19)	5.812 (2.288)	-6.276 (-2.471)

Table 4: Model 5365 Resistance Data

Full-Scale Speed (m/s (ft/s, knots))	**Model-Scale Speed (m/s (ft/s, knots))**	**Model Drag (N (lbs))**	**C_T x 1000**
3.1 (10.1, 6.0)	1.08 (3.53, 2.09)	9.96 (2.24)	3.75
4.6 (15.2, 9.0)	1.62 (5.30, 3.14)	22.42 (5.04)	3.75
5.4 (17.7, 10.5)	1.88 (6.17, 3.66)	34.38 (7.73)	4.23
6.2 (20.3, 12.0)	2.15 (7.06, 4.18)	44.62 (10.03)	4.20
9.3 (30.4, 18.0)	3.22 (10.58, 6.27)	97.77 (21.98)	4.09
13.3 (43.5, 25.8)	4.62 (15.16, 8.99)	175.88 (39.54)	3.58
15.4 (50.6, 30.0)	5.37 (17.63, 10.45)	212.18 (47.70)	3.19
18.0 (59.1, 35.0)	6.27 (20.57, 12.19)	265.60 (59.71)	2.94

Wave Cut Capacitance Probes

Wave cut data were obtained at model speeds representing full-scale speeds of 5.4, 9.3, 13.3, and 15.4 m/s (17.7, 30.4, 43.5, and 50.6 ft/s), or 10.5, 18, 25.8, and 30 knots. At least two runs were made for each speed. Figures 12 through 15 show typical results.

Wave resistance was computed from this data and C_w is compared to the results from the 1979 and 1992 testing in Figure 16. It can be seen that the all three tests show similar C_w.

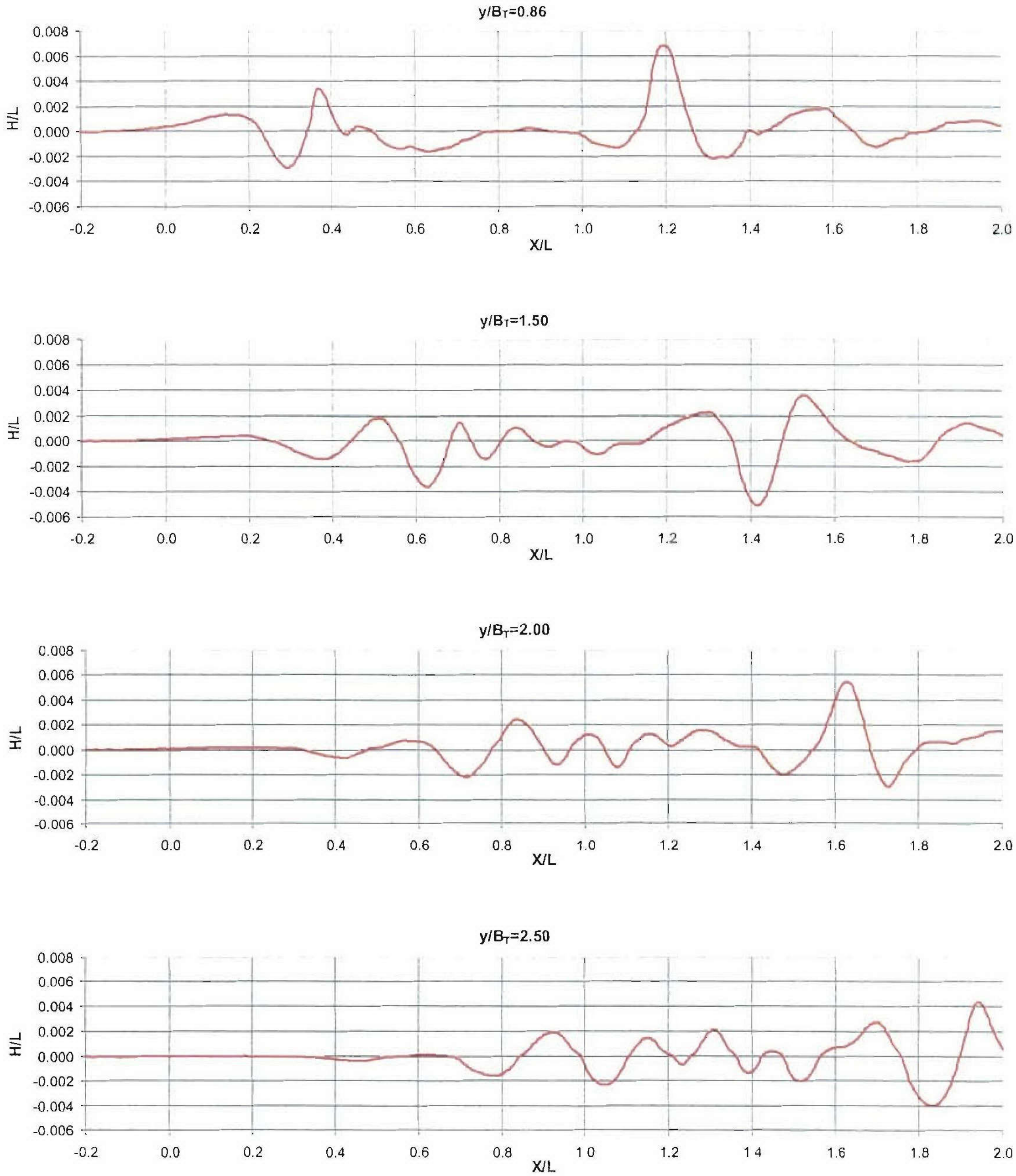


Figure 12: Wave cut records for Model 5365 at 1.88 m/s (6.17 ft/s).

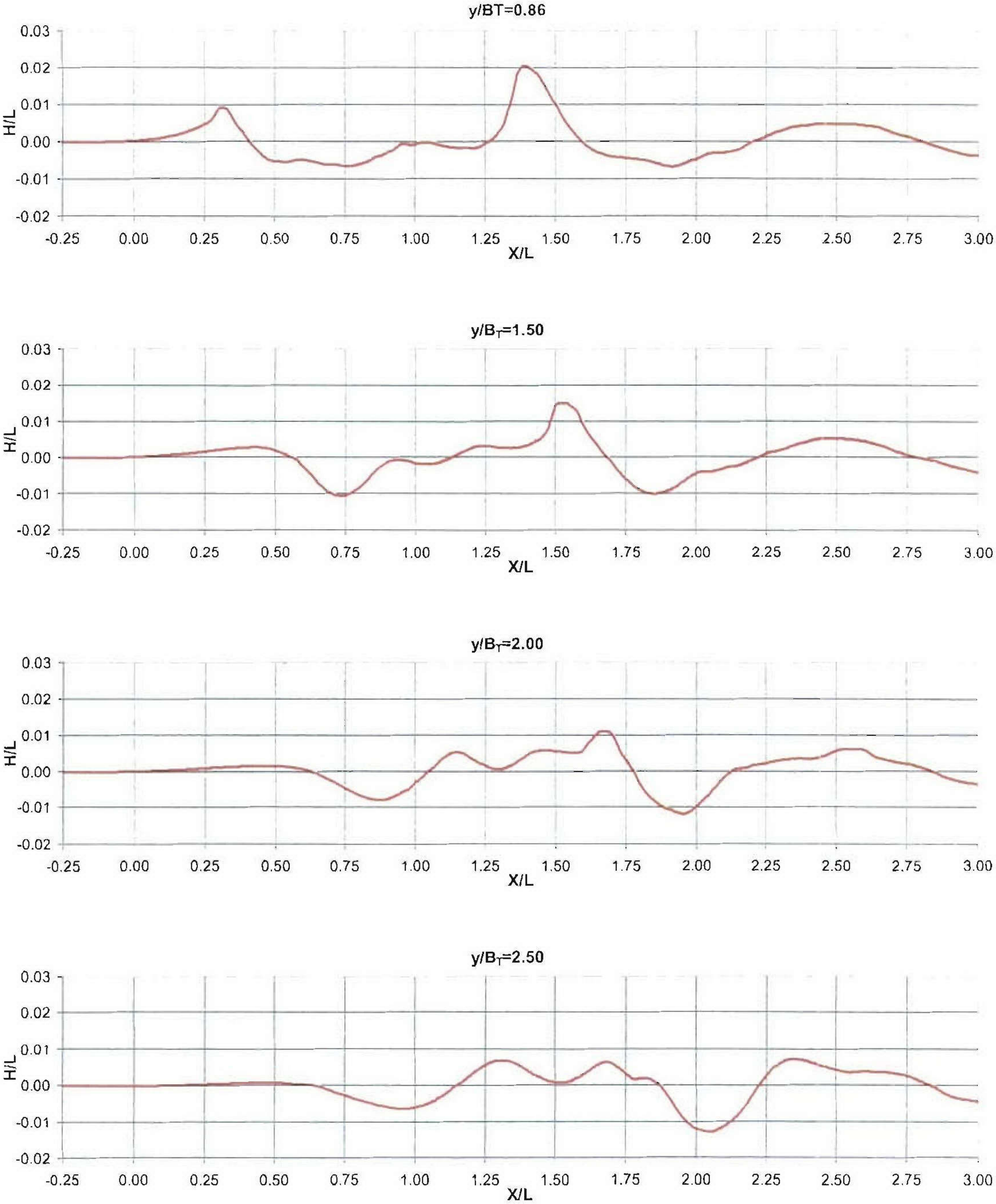


Figure 13: Wave cut records for Model 5365 at 3.22 m/s (10.57 ft/s).

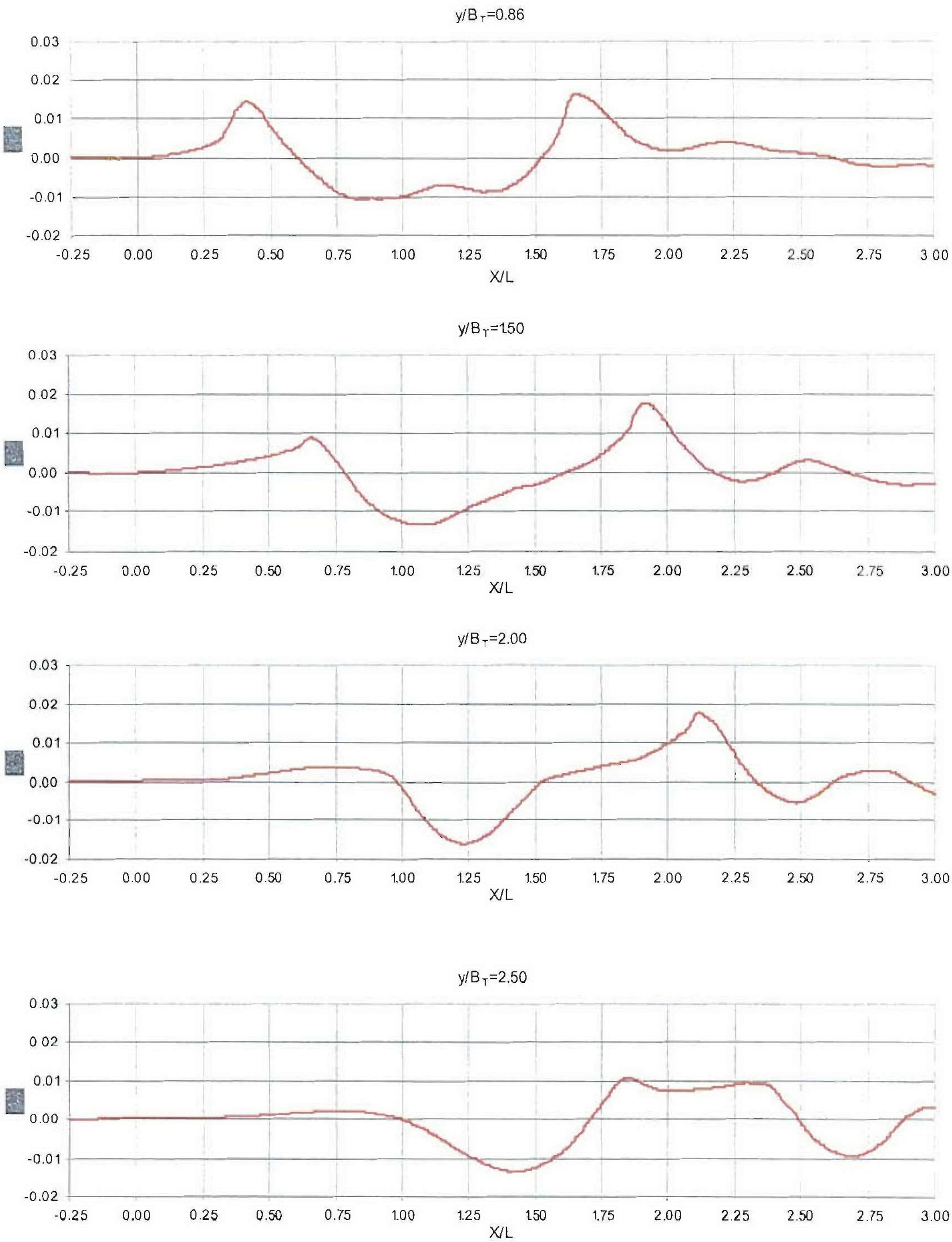


Figure 14: Wave cut records for Model 5365 at 4.62 m/s (15.16 ft/s).

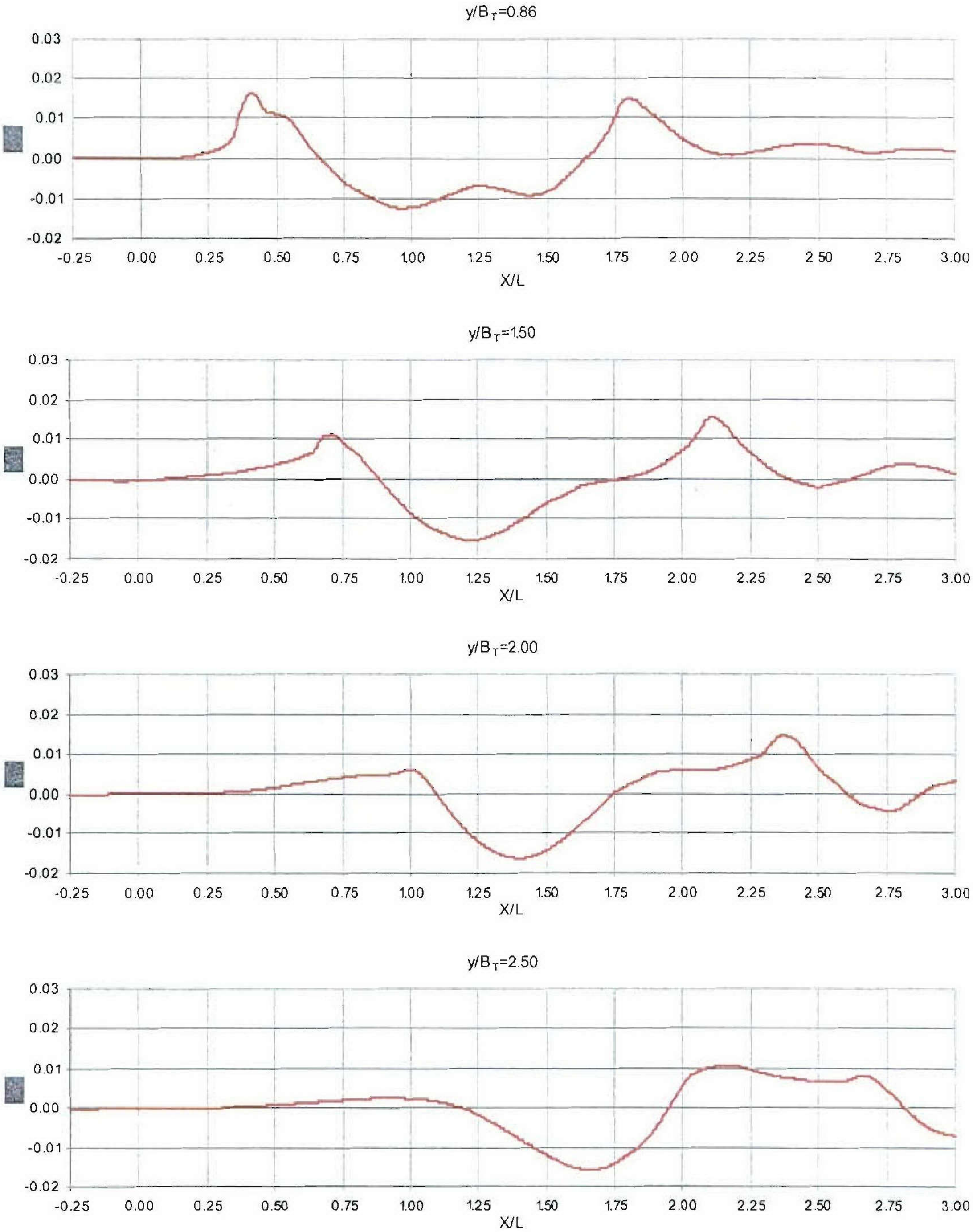


Figure 15: Wave cut records for Model 5365 at 5.37 m/s (17.63 ft/s).

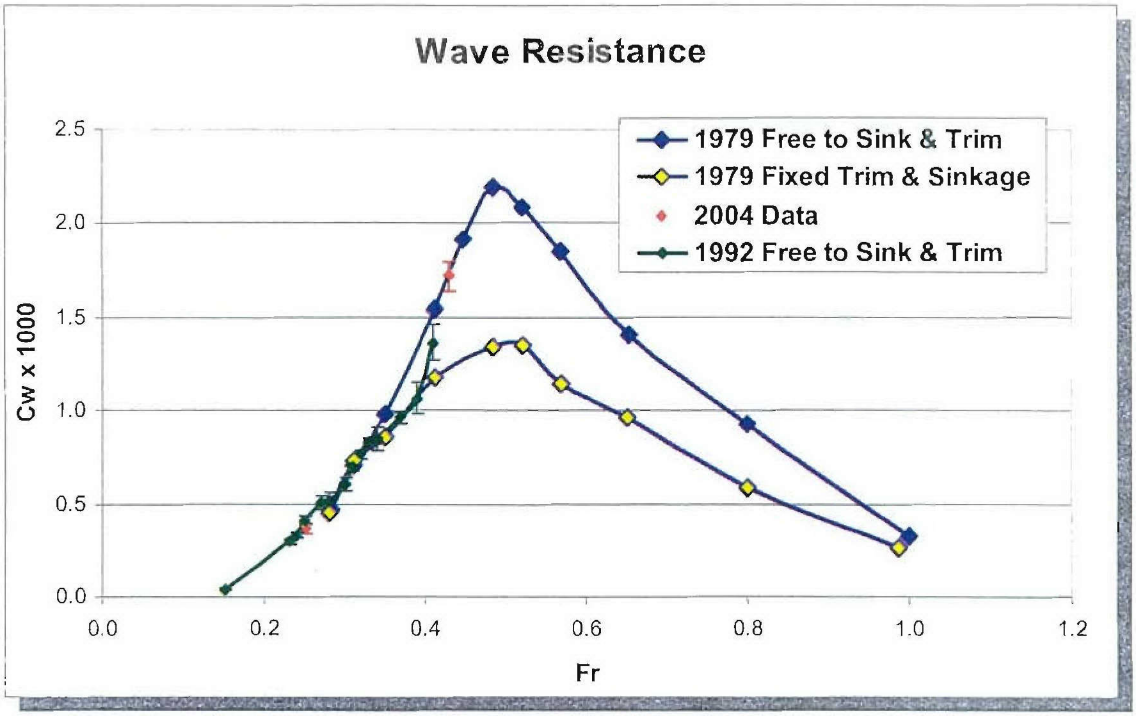


Figure 16: Coefficient of wave resistance for a range of Froude numbers.

Free-surface wave field topography

Free-surface wave field topography was generated by combining the QViz and finger probe results. QViz mapped out the region along the starboard side of the hull, while the conductivity probes were used to map out the free-surface wave pattern in the stern region of the model. All length scales in the figures are non-dimensionalized by the length of the model. The horizontal axis, "X/L", is zero at the bow stem of the model and positive aft of the model, and the vertical axis, "Y/L", is equal to zero at the model centerline. The data were obtained at speeds corresponding to full-scale speeds of 5.4, 9.3, 13.3, and 15.4 m/s (17.7, 30.4, 43.5, and 50.6 ft/s), or 10.5 18, 25.8, and 30 knots. The resulting contour plots are shown in Figures 17 through 20, in which the QViz data have been mirrored and shown on both sides of the hull.

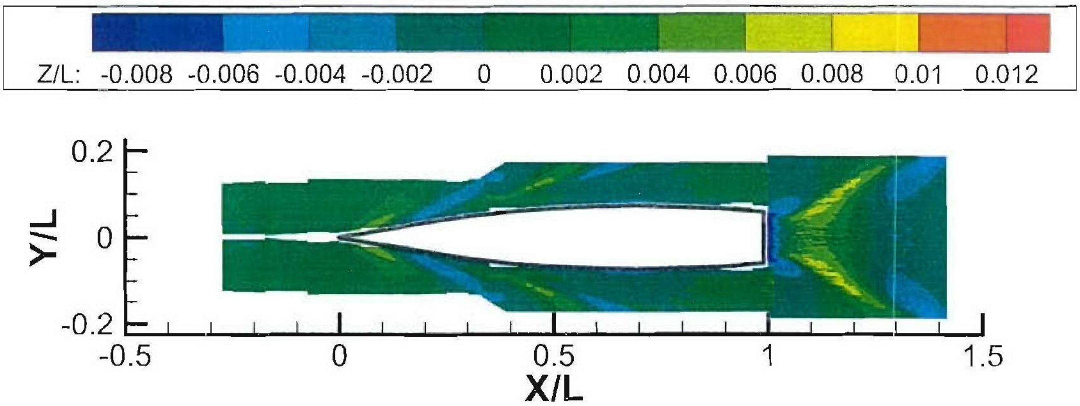


Figure 17: Wave field topography for Model 5365 at 1.88 m/s (6.17 ft/s), corresponding to 5.4 m/s (17.7 ft/s), or 10.5 knots, full-scale

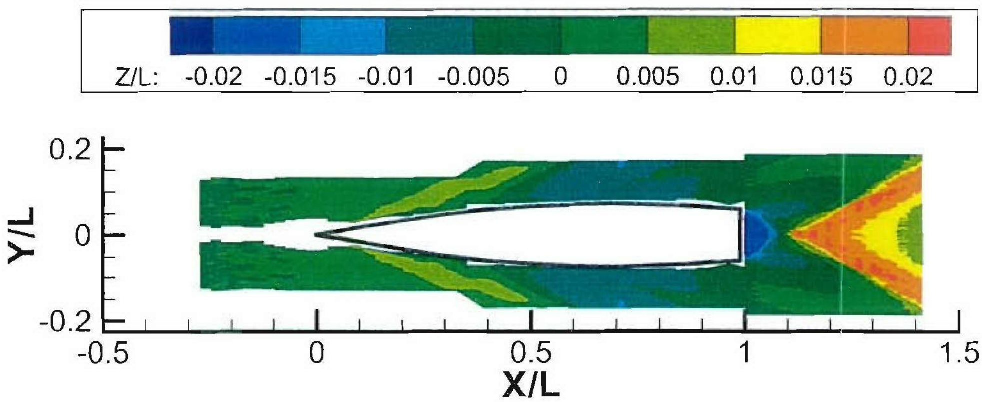


Figure 18: Wave field topography for Model 5365 at 3.22 m/s (10.58 ft/s), corresponding to 9.3 m/s (30.4 ft/s), or 18.0 knots, full-scale

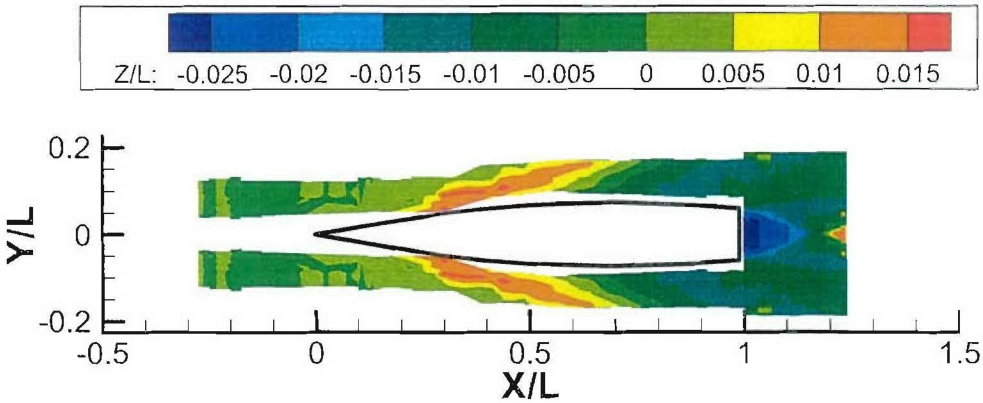


Figure 19: Wave field topography for Model 5365 at 4.62 m/s (15.16 ft/s), corresponding to 13.3 m/s (43.5 ft/s), or 25.8 knots, full-scale

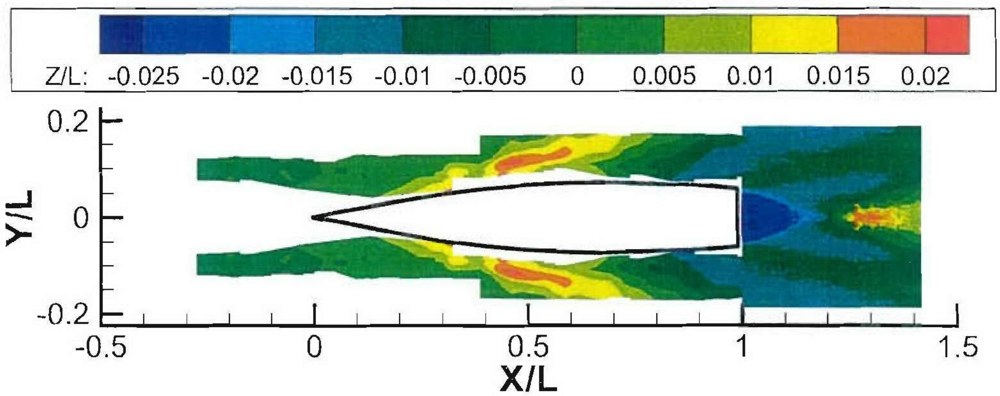


Figure 20: Wave field topography for Model 5365 at 5.37 m/s (17.63 ft/s), corresponding to 15.4 m/s (50.6 ft/s), or 30 knots, full-scale

Video

Still images taken from video are shown for both model and full scale tests of the R/V Athena, for speeds corresponding to full-scale speeds of 5.4, 9.3, and 13.3 m/s (17.7, 30.4, and 43.5 ft/s), or 10.5 18, and 25.8 knots (Figures 21 through 32). When comparing model to full-scale for the bow images, it appears that there is more spray at full-scale than model scale, with an increase in spray with increased speed. Stern images at 5.4 m/s (17.7 ft/s, 10.5 knots) are similar for model and full-scale, but more air seems to be entrained at full-scale. Stern image comparisons between model and full-scale for the two higher speeds show that there is significantly more spray at full-scale.

Figure 21: Bow image of Model 5365 during testing at 1.88 m/s (6.17 ft/s), corresponding to 5.4 m/s (17.7 ft/s), or 10.5 knots, full-scale

Figure 22: Bow image of full-scale R/V Athena during testing at 5.4 m/s (17.7 ft/s), or 10.5 knots

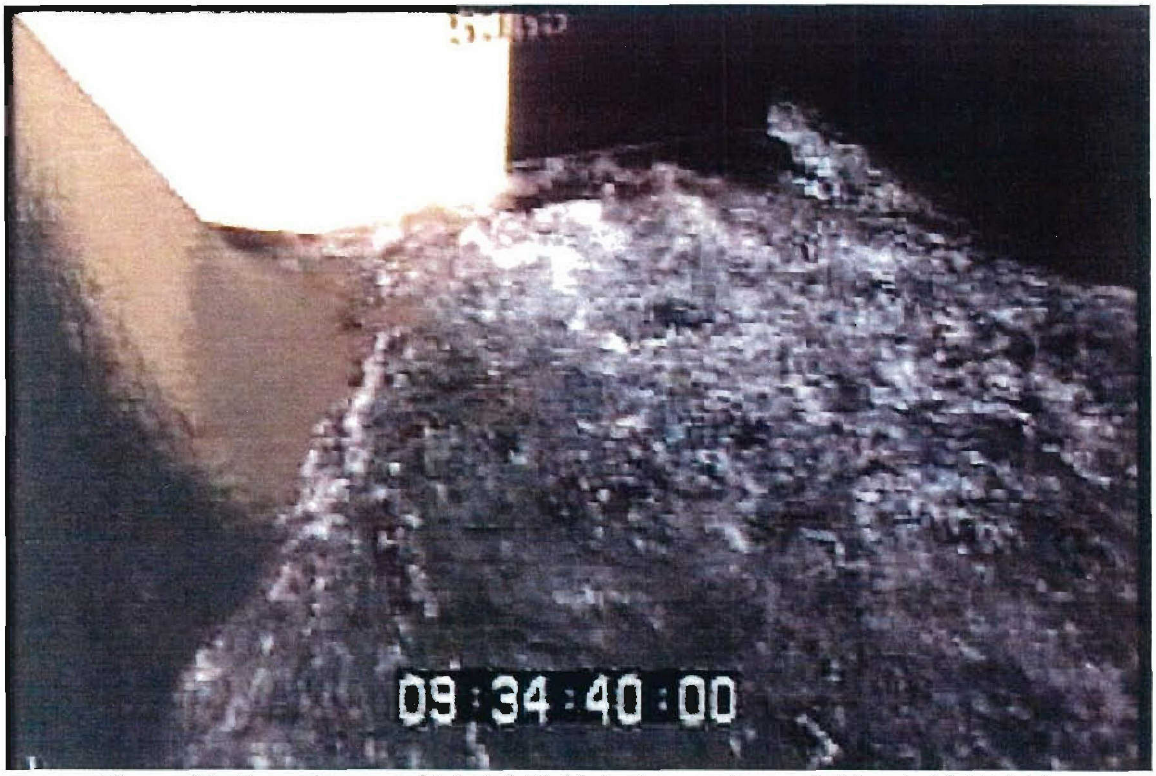


Figure 23: Stern image of Model 5365 during testing at 1.88 m/s (6.17 ft/s), corresponding to 5.4 m/s (17.7 ft/s), or 10.5 knots, full-scale

Figure 24: Stern image of full-scale R/V Athena during testing at 5.4 m/s (17.7 ft/s), or 10.5 knots

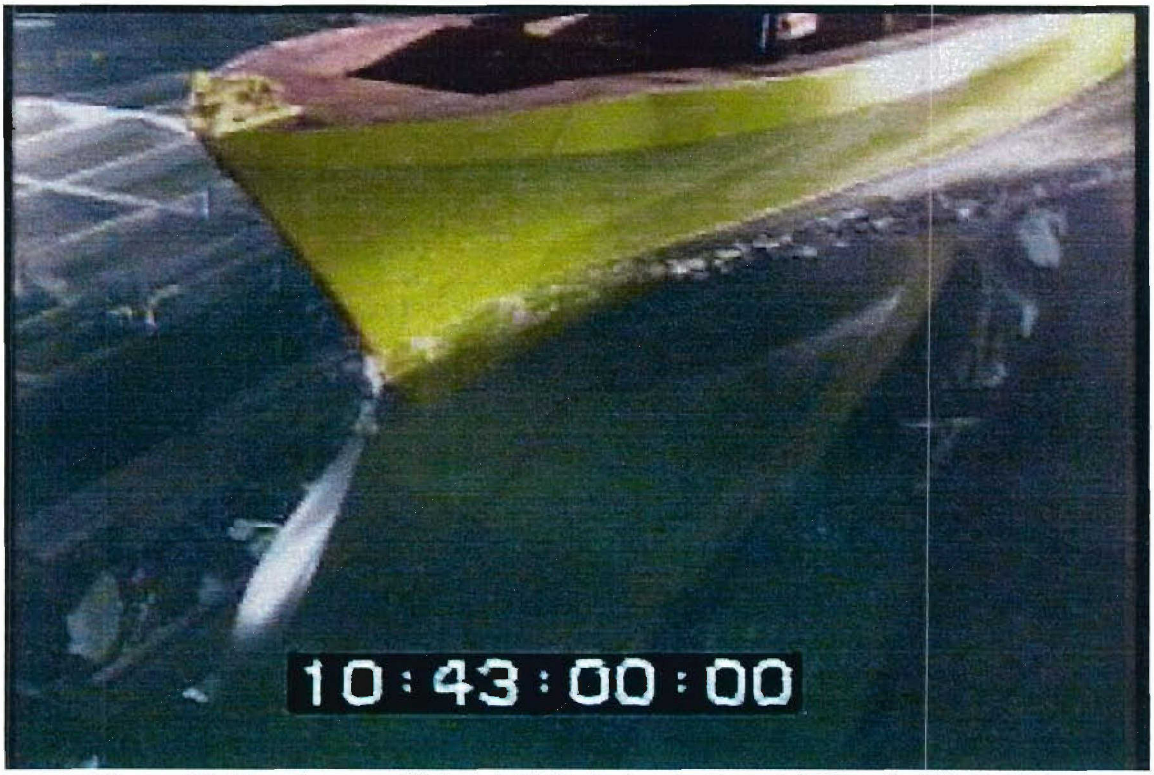


Figure 25: Bow image of Model 5365 during testing at 3.22 m/s (10.58 ft/s), corresponding to 9.3 m/s (30.4 ft/s), or 18.0 knots, full-scale

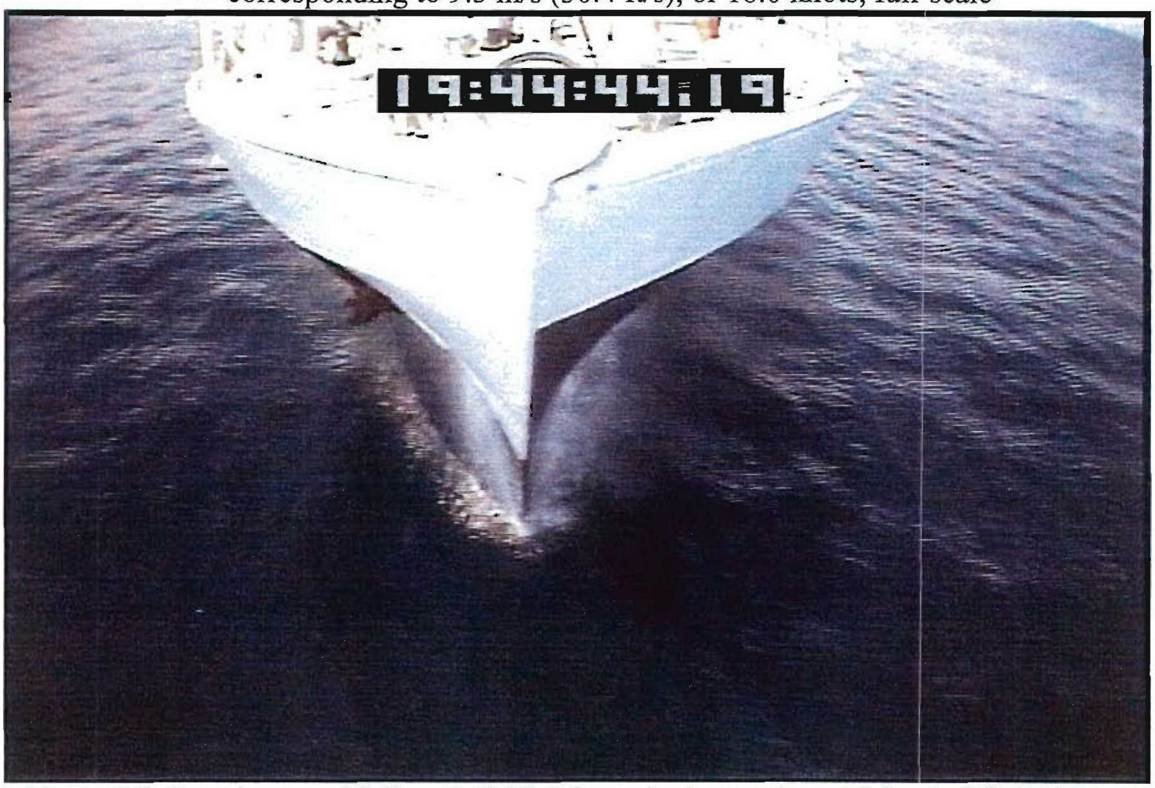


Figure 26: Bow image of full-scale R/V Athena during testing at 9.3 m/s (30.4 ft/s), or 18.0 knots

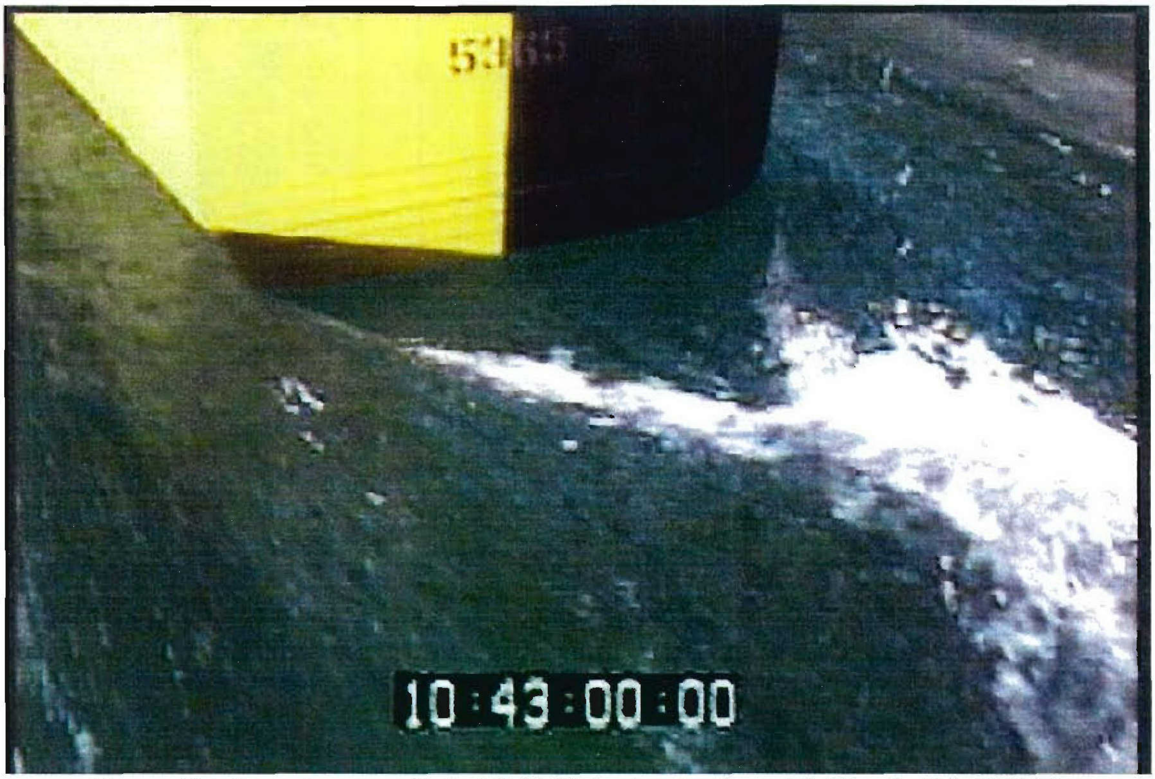


Figure 27: Stern image of Model 5365 during testing at 3.22 m/s (10.58 ft/s), corresponding to 9.3 m/s (30.4 ft/s), or 18.0 knots, full-scale

Figure 28: Stern image of full-scale R/V Athena during testing at 9.3 m/s (30.4 ft/s), or 18.0 knots

Figure 29: Bow image of Model 5365 during testing at 4.62 m/s (15.16 ft/s), corresponding to 13.3 m/s (43.5 ft/s), or 25.8 knots, full-scale

Figure 30: Bow image of full-scale R/V Athena during testing at 13.4 m/s (43.9 ft/s), or 26 knots, full-scale

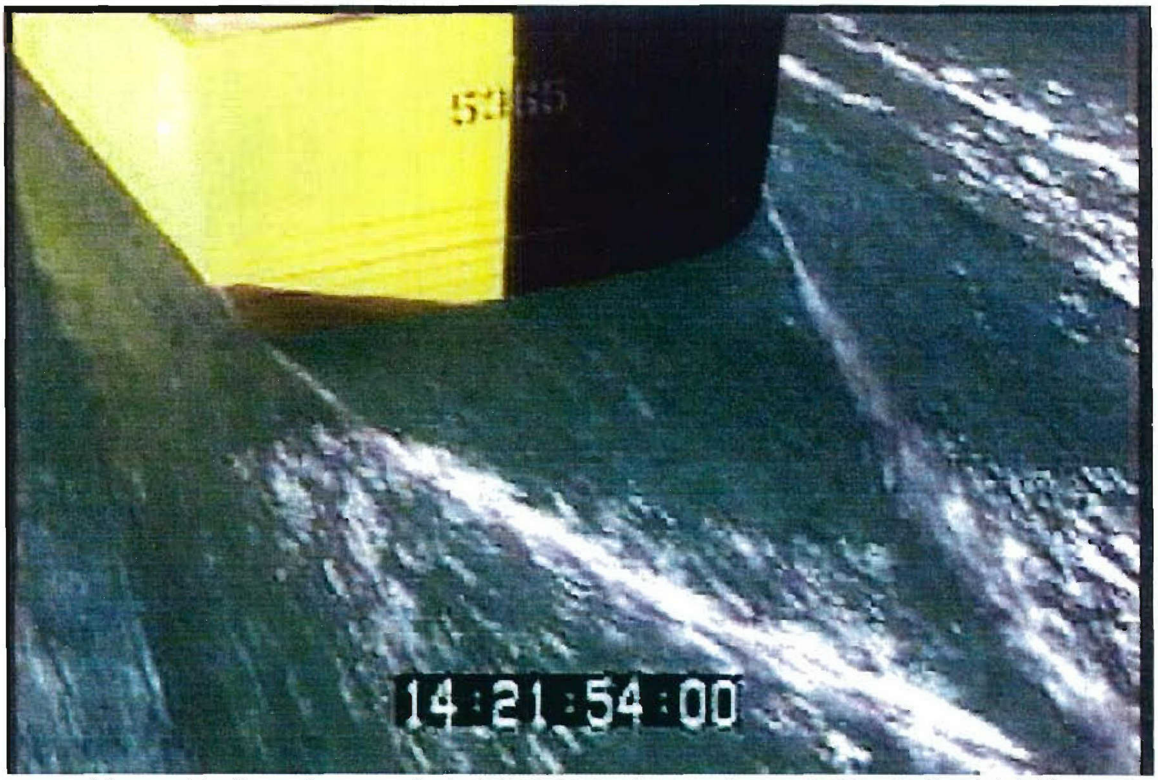


Figure 31: Stern image of Model 5365 during testing at 4.62 m/s (15.16 ft/s), corresponding to 13.3 m/s (43.5 ft/s), or 25.8 knots, full-scale

Figure 32: Stern image of full-scale R/V Athena during testing at 13.4 m/s (43.9 ft/s), or 26 knots, full-scale

CONCLUSIONS

Detailed measurements and characterization of the wave field around Model 5365 were completed and will be used during the 2005 ONR Ship Wavebreaking Workshop to evaluate the current capability of CFD codes to accurately predict the wave field and wave breaking generated from a ship at constant velocity. Detailed surface topography was measured at four speeds, corresponding to full-scale speeds of 10.5, 18, 25.8 and 30 knots. Longitudinal wave cuts were also made at these speeds and were used to compute wave resistance for these four speeds. C_w was in good agreement with the results reported by Jenkins[5].

Sinkage, trim, and resistance were measured over a range of Froude numbers (0.14 to 0.82). The sinkage and trim are also in good agreement with Jenkins[5] as well as previously unpublished data acquired in 1992. The measured total resistance is systematically less than the previously measured data, pointing to an error in calibration or possible stiction in the tow post/grasshopper. While an error in speed is another possible explanation, this seems unlikely, in that the wave cuts and sinkage and trim data are in good agreement with Jenkins[5].

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APPENDIX A

MODEL 5365 1979 DATA

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APPENDIX A

Table A1: Sinkage and Trim and Resistance Data for 1979

Speed		Fr	Forward Perpendicular Trim (in)	Aft Perpendicular Trim (in)	Free to Sink & Trim Fx (lbs)	Fixed Trim Fx (lbs)
Full-Scale (kts)	Model Scale (kts)		+ bow up, - bow down	+ bow up, - bow down		
11.7	4.08	0.280	-0.168	-0.302	13.5	11.6
13.0	4.52	0.310	-0.269	-0.392	16.0	13.6
13.1	4.55	0.312	-0.269	-0.403	16.2	13.7
14.7	5.11	0.350	-0.336	-0.549	19.2	16.2
17.2	5.98	0.410	0.336	-1.120	28.8	22.8
20.1	7.00	0.480	0.840	-1.938	41.4	31.8
21.8	7.59	0.520	1.277	-2.196	47.4	37.1
23.9	8.31	0.570	1.546	-2.252	54.0	43.9
27.2	9.48	0.650	1.759	-2.184	64.7	55.5
33.5	11.67	0.800	1.815	-1.972	87.3	79.6
41.9	14.59	1.000	1.546	-1.322	124.7	120.9

Table A2: Wavemaking Resistance Data for 1979 Free to Sink & Trim

Full-Scale Speed (kts)	Model-Scale Speed (kts)	Fr	Cw x 1000
11.8	4.09	0.282	0.465
13.0	4.53	0.312	0.700
14.6	5.10	0.351	0.985
17.2	5.98	0.412	1.546
18.7	6.50	0.448	1.912
20.2	7.03	0.484	2.192
21.7	7.56	0.521	2.083
23.8	8.28	0.570	1.851
27.2	9.48	0.653	1.407
33.4	11.62	0.800	0.931
41.7	14.52	1.000	0.325

Table A3: Wavemaking Resistance Data for 1979 Fixed at Zero Trim and Sinkage

Full-Scale Speed (kts)	Model-Scale Speed (kts)	Fr	Cw x 1000
11.7	4.08	0.281	0.451
13.0	4.53	0.312	0.734
14.6	5.08	0.350	0.858
17.2	5.98	0.412	1.182
20.2	7.03	0.484	1.342
21.7	7.56	0.521	1.350
23.8	8.28	0.570	1.150
27.2	9.45	0.651	0.968
33.3	11.60	0.799	0.584
41.2	14.35	0.988	0.258

Table A4: Sinkage and Trim and Resistance Data for 1992 Free to Sink and Trim

Speed		Fr	Free to Sink & Trim	Forward Perpendicular Trim (in)	Aft Perpendicular Trim (in)
Full-Scale (kts)	Model Scale (kts)		Fx (lbs)	+ bow up, - bow down	+ bow up, - bow down
5.0	1.75	0.120	2.6	0.037	0.066
6.3	2.18	0.149	4.0	0.005	0.215
7.9	2.75	0.189	6.8	0.065	0.145
7.9	2.76	0.189	6.6	0.066	0.139
9.6	3.34	0.229	10.0	0.106	0.255
10.0	3.49	0.239	10.9	0.050	0.189
10.4	3.63	0.249	12.5	0.102	0.303
11.3	3.92	0.269	15.1	-0.136	0.109
11.7	4.07	0.279	16.2	-0.568	-0.299
12.5	4.36	0.299	18.7	0.086	0.484
12.9	4.50	0.308	20.2	0.044	0.504
13.4	4.65	0.319	21.3	0.046	0.550
13.8	4.79	0.328	22.7	0.034	0.585
14.2	4.94	0.339	23.9	0.040	0.621
14.2	4.94	0.338	23.8	0.039	0.644
14.6	5.08	0.348	25.2	0.021	0.734
15.4	5.37	0.368	28.3	-0.053	0.894
16.3	5.67	0.388	32.5	-0.271	1.204
16.3	5.67	0.388	32.5	-0.259	1.192
17.1	5.96	0.408	36.9	-0.524	1.516

Table A5: Wavemaking Resistance Data for 1992 Free to Sink and Trim

Full-Scale Speed (knots)	Model-Scale Speed (knots)	Fr	Cw x 1000
6.26	2.18	0.15	0.04
9.59	3.34	0.23	0.29
10.01	3.48	0.24	0.33
10.43	3.63	0.25	0.41
11.26	3.92	0.27	0.50
11.72	4.08	0.28	0.52
12.51	4.36	0.30	0.61
12.93	4.50	0.31	0.70
13.35	4.65	0.32	0.76
13.76	4.79	0.33	0.83
14.18	4.94	0.34	0.85
15.43	5.37	0.37	0.96
16.27	5.66	0.39	1.07
17.14	5.97	0.41	1.37

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